NACA

RESEARCH MEMORANDUM

METEOROLOGICAL PROBLEMS ASSOCIATED WITH COMMERCIAL TURBOJET-AIRCRAFT OPERATION

By a Working Group of the NACA
Subcommittee on Meteorological
Problems

NACA Headquarters

NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS

WASHINGTON
June 21, 1955

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SUMMARY

Meteorological requirements and problems anticipated with the operation of commercial turbojet aircraft have been analyzed and evaluated. Discussions concerning problems of temperature, wind, pressure, ceiling, visibility, cloud and clear-air turbulence, icing, and communication are included in this study.

Consideration has been given to those characteristics of turbojet aircraft which have a direct bearing upon the nature of the weather service required for safe, efficient, and economical operation. These characteristics are high cruising speed, high cruise level, relatively high fuel consumption, and engine performance sensitive to temperature and air density.

No new requirements or problems are expected even though operating altitudes and speeds are increased and forecast error limitations are more critical, especially in the airport terminal area, for the turbojet as compared with piston-engine aircraft. The recommended solutions for the meteorological problems involve adequate instrumentation, improved communications facilities, reliable techniques for analysis and forecasting, and the successful application of research results.

INTRODUCTION

The advent of commercial turbojet-aircraft operation in this country necessitates evaluating the meteorological problems anticipated and establishing procedures, if necessary, to cope with these problems. Therefore, the Subcommittee on Meteorological Problems of the National Advisory Committee for Aeronautics formed a working group, the activities of which were based on the following objectives:

(a) To collect available information, both foreign and domestic, concerning meteorological requirements for turbojet-aircraft operations

(b) To analyze and evaluate the information in terms of meteorological problems

(c) To specify the more important problems and determine their priority

(d) To recommend, through the parent committee, needed changes in current procedures and meteorological services or additional research which would solve or alleviate these problems

The membership of the working group was composed of personnel who were either appointed by the chairman of the subcommittee or appointed by members of the subcommittee to serve for their organizations. (See appendix A.)

At the outset, the members decided that the comparable problems of turboprop-aircraft operations would not be considered separately since the meteorological problems pertaining to this type would lie somewhere between those of the conventional and those of the turbojet aircraft. In addition, it was agreed that the problems would be considered from the viewpoint that jet transports will not be given preferred treatment in traffic patterns, holding situations, and diversion to alternate terminals.

In the sections which follow, the overall meteorological problems anticipated for turbojet-aircraft operations are presented. Recommendations to improve or extend existing service are suggested and justified on the basis of safety, efficiency, economy, and practicability. Particular meteorological and relevant operations problems are discussed in detail and some practical solutions are included. Considerations of these problems through research and development are also given. Detailed comments on certain aspects of forecasting for jet-aircraft operation, a discussion of special ceiling and visibility problems, and an outline of facilities for an idealized station are presented as appendixes.

A bibliography of reports pertinent to aircraft operating problems is also included.

STATEMENT OF GENERAL PROBLEM

The turbojet transport has four important characteristics which create operating problems that are considerably different from those of conventional piston-engine aircraft and therefore have a direct bearing upon the nature of the weather service which will be required to operate this aircraft safely, efficiently, and economically. These characteristics, which may result in new requirements for meteorological services beyond those currently required for piston-engine aircraft, are:

(1) Cruising speed in excess of 450 knots

(2) Optimum cruising level above 30,000 feet

(3) Relatively high fuel consumption, especially below optimum cruising altitude

(4) Engine performance particularly sensitive to temperature and air density

The higher cruising speed of the turbojet greatly magnifies the effect of cloud and clear-air turbulence, in relation both to the stresses imposed upon the airframe and to the personal discomfort of the occupants. Airborne radar should make it possible to minimize most turbulent areas associated with well-developed cumuloform clouds. However, clear-air turbulence remains a problem and requires the development of more adequate methods of observing and forecasting.

At the higher cruising levels of these aircraft, data are relatively sparse, meteorological experience is limited, and forecasts are less adequate than at current transport-aircraft cruising levels. These altitudes are near the level of the maximum jet-stream flow in the middle latitudes, and winds in excess of 200 knots will not be uncommon in the jet-stream cores which may extend for several hundred miles along any given route. Despite its high cruising speed, the turbojet will therefore be subject to occasional marked deviations from schedule, but this problem will gradually be minimized as cruising speeds are increased.

The relatively high fuel consumption and high fuel-to-payload ratio of the turbojet demand more accurate route and terminal forecasts. Markedly increased fuel consumption at levels below optimum cruising altitude leaves very little flexibility in choice of cruising level. Because of the excessive amount of fuel required to divert to an alternate terminal after landing is attempted at destination, more accurate and representative observations and forecasts of terminal conditions are needed.

The thrust produced by a turbojet engine is a function of the mass air flow through the engine and therefore thrust decreases as air density decreases or, at constant pressure altitude, as temperature increases. This loss of thrust at higher than standard temperatures adversely affects take-off and may necessitate a reduction in payload if take-off weight is limited by inadequate runway length. Forecasts of temperature at the surface will therefore be required for operational planning purposes.

DISCUSSION OF PARTICULAR PROBLEMS

SURFACE TEMPERATURE, PRESSURE, AND HUMIDITY

Statement of Problem

Temperature and pressure at engine intake level and air density at wing level are vital in determining engine performance (thrust or power) and aerodynamic lift, respectively. In conjunction with the surface wind, these parameters control maximum allowable take-off weight and required runway length. In the case of the DeHavilland Comet I aircraft, for example, a change of 10° F near sea level under certain critical conditions is the equivalent of approximately 2,000 pounds in maximum allowable take-off weight or nearly 400 feet in runway roll.

With regard to securing measurements of these parameters, the determination of temperature data which are representative of the runway site poses the only serious problem. At times, in some locations, runway temperatures at intake level have been as much as 10° to 15° F higher than the temperature measured at the standard meteorological shelter, but the difference will generally fluctuate. Since the turbojet engine is so sensitive to temperature at take-off, the measurement of temperature representative of runway conditions is essential. The critical conditions referred to include such things as short runways, high surface temperatures, low air density, and adverse surface-wind conditions.

With regard to the other parameters, pressure and vapor pressure may be considered generally homogeneous in a given horizontal plane for an area the size of an airport. Therefore, the measurements of these parameters in the standard meteorological manner may be considered representative. However, humidity appears to have no significant effect on the take-off performance of turbojet aircraft.

Discussion

In the past, temperature measurements representative of runway conditions were not a vital concern because the performance of conventional-type aircraft is not particularly affected by relatively small temperature differences. With the advent of jet aircraft, however, the Armed Services, who operate most of the jet aircraft in the United States, found that under certain critical conditions they specifically needed runway temperatures in order to use performance charts and to evaluate maximum allowable take-off weight. Studies of temperature differential between the meteorological shelter and the engine intake level over the runway have shown that some observations made in shelters located for synoptic representativeness or for convenient access are extremely poor for indicating the temperature over the take-off zone.

Conclusions

There are no methods currently in use which provide precisely the thermal data required for efficient take-off of civilian jet aircraft. The solution of this problem therefore appears to lie in the development of suitable techniques and instruments for measuring the temperature which is representative of engine intake level over the runway.

Proposals

In considering the following proposals, it should be realized that the data secured specifically for application to jet aviation may not fulfill the requirements of other fields, for example, synoptic meteorology. This may necessitate measurement with appropriate techniques under different conditions of environment. Also, it should be assumed that, wherever necessary, telecommunication systems will be used.

(1) A survey of location and exposure of the instrument shelters at airports where jet aircraft will operate should be made to ascertain the degree of representativeness which each yields in regard to thermal conditions over the runway. Those shelters which are observed to give relatively large or significant discrepancies should be relocated to a site which permits the obtainment of better readings for this purpose.

(2) A study should be made to determine a practical method of measuring temperature, possibly away from the airstrip itself for reasons of safety, so that the resulting observations closely represent the thermal conditions at the engine intake level over the runway. The development of such a method should be made contingent upon the results of the study.

(3) A study should be made to determine the practicability of devising a method for obtaining the integral mean temperature along a path at the engine intake level over the runway itself. An example of such a method involves the determination of the velocity of sound, taking wind velocity and humidity into account if necessary. From the velocity of sound, the average temperature along the path is calculated.

(4) In cases where a satisfactory solution is not achieved under the foregoing proposals, a system of corrections determined empirically as a function of concurrent local conditions should be applied to the readings observed in the instrument shelter (located as in (1) above) in order to approximate the values required for aircraft operations.

SURFACE WIND

Statement of Problem

The surface wind at aircraft level is important as a controlling factor in the determination of maximum allowable take-off weight and length of runway required for jet aircraft to become safely airborne.

Like temperature, wind at many air terminals is measured at a location which is not sufficiently representative of the wind over the runway. At one airport, a limited test made when the tower winds were around 20 knots showed tower winds to be 25 percent to 50 percent stronger than the corresponding winds on the runway. At another base, under light wind conditions, the direction of the wind at the tower level sometimes differed from that over the runway at aircraft level by as much as 180°. These two cases indicate that the measurement of wind under present exposures does not necessarily yield values which are indicative of the winds actually encountered on the runway.

Further, there is a need for determining more about the type of surface-wind data that will be required for jet operations. The problems to some degree stem from the variations of the surface wind, both in time and space.

Discussion

Because of the current economic aspects of turbojet-aircraft operations and the overall performance of these aircraft, the surface wind has become more critical than it has been for the operation of conventional aircraft. Thus, for jet-aircraft operations it will be necessary to observe and forecast the wind at the place of take-off to a more accurate degree than was previously necessary. The wind measured at the tower can no longer be accepted as being representative of the wind that the jet aircraft will encounter at take-off.

Under a given situation of runway length, orientation, temperature, and so forth, the expected take-off headwind conditions play a significant role in the calculation from operational performance charts of the total allowable take-off weight. In view of the high rate of fuel consumption of turbojet engines, which may be from 2 to $3\frac{1}{2}$ times as much as that for reciprocating engines, the total fuel load at take-off can approach 50 percent of the total weight. This means that, in order for the aircraft to become airborne with the greatest possible payload, the effective take-off winds should be accurately forecast. With runway length restricted and surface temperature constant, an accurate forecast of a 10-knot increase in surface headwinds may mean several tons more payload (see appendix B). The prime requisite for attainment of this wind forecasting goal is accurate wind observations at the area of take-off, and the second need is for adequate techniques for such wind forecasting.

With reference to the problem of obtaining the necessary wind observations, it is necessary to consider appropriate instrumentation to determine the effective wind velocity and gustiness in terms of components relative to the pertinent runway. This involves questions of equipment having locations, heights, and exposures relative to the runway, ground, and obstacles such as to yield results most representative of the effective wind conditions at the take-off area. Among the factors that should be considered are (a) the appropriate length of time over which the wind measurements should be averaged for obtaining components, (b) the characteristics of gusts and suitable methods for describing these characteristics, (c) the procedures, terminology, and codes adopted for reporting the wind phenomena, (d) the consideration of lapse rate and other turbulence parameters, and (e) the techniques of analysis of the data best designed to assist the pilot, the control-tower operator, and the forecast meteorologist in carrying out their respective functions.

With regard to the solution of the problem of wind forecasting that will satisfy the needs of jet-aircraft operations, the procedures, requirements, and tolerances will probably depend on the time, range, and application of the forecast, for example, 12-hour operational planning forecast, 1-hour short-term flight-calculation forecast, and final verification, just prior to take-off. (See appendixes B and C.) This may necessitate further consideration of frontal accelerations and intensifications, the coupling of surface winds with those at gradient and upper levels, effects of various cloud types on vertical transport of momentum, lapse rates, wind shear, and terrain effects.

Conclusions

The surface-wind data as currently obtained for aviation interests leave much to be desired for the efficient operation of civilian jet aircraft. The shortcomings lie both in the lack of representativeness of the surface-wind observations for runway conditions and in the lack of knowledge as to what form the wind data should take to be of the most use to jet-aircraft-operations personnel. The solution of this problem seems to demand a study of the requirements of surface-wind data necessary for jet flight. Based on the findings of such a study, development of a workable program will require appropriate instruments properly exposed for obtaining representative wind data, adequate procedures for the handling and rapid dissemination of such data, and effective techniques of forecasting to fulfill these needs.

Proposals

(1) At airports where jet aircraft will operate, a survey should be made of existing locations and exposures of wind measuring instruments to determine how representative the wind data are of the runway conditions. Those locations which are found to give significantly different values from the required ones should be relocated to a site where observations more nearly satisfactory for this purpose may be obtained. Reevaluation of the quality of the site may be necessary from time to time.

(2) A study should be made to determine what the actual requirements of jet-aircraft operations are with regard to effective surface wind over the runway. Dependent upon the findings of such a study, practical methods should be investigated and developed for obtaining and processing wind measurements so that these requirements will be satisfied. Safety considerations will probably dictate that measurements be made at some distance from the runway.

(3) An investigation should be made to determine the practicability of devising different methods of measuring the effective surface wind over the runway itself. (See proposal (3) of the section entitled "Surface Temperature, Pressure, and Humidity.")

(4) In cases where no satisfactory solution is achieved under the preceding proposals, an effort should be made to develop a system of empirically determined corrections which when applied to the wind observations would yield a closer approximation to the values required for turbojet-aircraft operations.

CEILING AND VISIBILITY

1 cm radar along glidepath

Statement of Problem

Ceiling and visibility conditions have vital influences on the economy, efficiency, and safety of all aircraft flight operations. For turbojet aircraft, fuel consumption is considerably higher at low altitudes than at normal cruising altitudes; therefore, a descent from cruising level toward a terminal, followed by a missed approach, uses up so much fuel that the range possible to an alternate airport suffers a marked decrease compared with the maximum range possible if diversion had been begun at the cruising level. This range loss becomes greater if low-level holding is involved.

When cloud and visibility conditions are restrictive, representative data regarding ceiling and visibility are essential for making optimum selections for lateral separations of aircraft, take-off times, safe traffic density, acceptance rates at terminals, landing times, and so forth. Provision of ceiling and visibility observations, without reliable forecasts, is not sufficient. Reference 1 states that, for jet operations, the aim is to provide a service of such a standard that descent is never started toward a terminal the conditions at which subsequently deteriorate to such an extent as to preclude a landing.

Discussion

The problems pertaining to ceiling and visibility are the same in kind for jet aircraft as for piston-engine aircraft, but the requirements based on economic considerations are more severe for the former. Most important are the requirements concerning reliability of forecasts and currency of advices transmitted to the pilot, especially minimization of delay between times of receipt and issuance.

Appendix C presents a more or less technical discussion of some of the major aspects of the ceiling and visibility problems involved in meeting the more severe requirements of turbojet aircraft.

It is apparent that difficulties must be faced in providing the necessary services for localities where there is a relatively frequent occurrence of extreme variability in regard to weather conditions affecting the approach and terminal areas. Representative observations are required at suitable intervals from a distribution of stations designed to fulfill the various forecasting requirements in regard to the type of data transmitted, locality, range, and time. Reliable forecasts of terminal and alternate-airport conditions are needed in advance of scheduled departures for planning and clearance purposes.

After the aircraft is airborne, there is a need to supply its commander with additional weather information regarding conditions at terminal or alternate airports or both. Three important times when such reports will be opportune are as follows:

(1) At the time just before the point of no return (critical point) is reached

(2) At the time just before a descent will normally be begun

(3) At the time during an approach just before the critical altitude is reached

Reliable communication facilities to permit direct contacts between ground advisors and pilots are absolutely essential in supplying the information needed.

The forecast elements most needed for successful approach and landing operations are the slant visual ranges pertaining to the approach zone and the runway visual range. It is considered that slant visual range from the glide path is expressed in terms of the maximum altitude below which the approach may be continued with visual contact with the ground. The targets observed by the pilot for this purpose may be as diverse as recognizable arrays of buildings, roads, fields, approach lights, threshold lights, runways, and runway lights. No single slant-range value applies to all. The problem is how to determine the most representative value.

Various schemes have been contemplated to this end. One proposal, based on tests at MacArthur Airport, New York, is to use a combination of instruments, including a rotating-beam ceilometer installed near the middle marker, a transmissometer installed near the end of the runway, and certain photometric equipment which will indicate the illumination incident on the ground and the brightness of the background against which the pilot sees the runway. It is considered that the indications from the instruments, after suitable processing, may be referred to certain charts expressing the desired results as a correlation on a probability basis, for visual slant range under given weather categories, such as conditions of low clouds, radiation fog, and snow. However, this proposal has important limitations, in part because the instruments do not really yield measures of the optical conditions in the free air well above the area sampled by them and in part because the assumptions underlying the correlations are not always fulfilled.

Serious problems confront meteorological services in regard to the measurement of actual slant visual range under instrument conditions. Thus, if the lower atmosphere involved is not horizontally homogeneous or if a steady state does not exist, no reasonably simple slant-range relationship or measuring system will apply. A slant-range measuring system is currently in process of development by the Naval Research Laboratory using photomultiplier tubes and searchlight projectors. However, Middleton (see ref. 2) has made calculations which indicate that presently available photomultiplier tubes will probably not yield perceptible signals for the purpose when dense fog prevails. Hence, until such tubes are made vastly more sensitive or until the intensity of available searchlight projectors is greatly increased, there will be limitations on the use of the system.

When marked heterogeneity or an unsteady state exists in the atmosphere from an optical standpoint, there exist variabilities in slant visual ranges and in runway visual ranges which should be taken into account. This may be done by expressing results in terms of probabilities.

The concept underlying this may be gained from an example referring to a given weather situation in which the 95-percent probability value for the threshold contact height is 250 feet. That is, for approaches made under the given conditions the pilots are likely to establish visual contact with the runway threshold at or above 250 feet in 95 out of 100 approaches. In the remaining 5, the contact is likely to be established below 250 feet.

Conclusions

(1) Continued laboratory research and development, in conjunction with field tests, are necessary to determine the most suitable and best methods of observing, recording, calculating, assessing, and reporting (a) the ceiling, (b) the various slant visual ranges from aircraft pertinent to achieving maximum approach success at runways under different conditions, and (c) the horizontal runway visual range under a diversity of situations.

(2) The complex problems of forecasting ceiling and visibility are so related to the considerations underlying the observation of the pertinent elements that it seems desirable to have special research activities looking to developments in these fields of forecasting.

(3) Variabilities in respect to various aspects of clouds, precipitation particles, suspensoids, and light conditions are always present to affect the ability of pilots to perform visual tasks during an approach. These variabilities impose limitations on predictability of how far objects or lights may be detected or recognized under critical conditions. For this reason, the expression of relevant forecasts on a probability basis is justified.

Proposals

The following proposals are submitted:

(1) A project should be established for research and development relating to the methods of measuring, observing, recording, assessing, and evaluating all significant parameters governing ceiling and visibility (including slant visual range) pertinent to approach and landing success.

(2) The development of basic horizontal- and slant-visibility theories pertinent to nonhomogeneous conditions as regards transmission of light and luminances of underlying surface foreground and background, with background at finite distances, should be encouraged; the theories should be tested in laboratory and field.

(3) A laboratory simulated-flight project should be initiated to measure the psychophysical parameters, such as background luminance and glare sources, and related physical factors, such as rain on windshields, which affect the vision of pilots; results should be tested by limited actual flights.

UPPER LEVEL TEMPERATURES

Statement of Problem

Temperature anomalies affected the range of the Comet I and other earlier design turbojet aircraft a small but significant amount. With later design turbojet aircraft, however, the effect of temperature on range is negligible.

The measurement of upper level temperatures to within at least $\pm 1^\circ$ C is nevertheless required for a purpose which is connected with flight operations but in a less obvious manner. This purpose is to determine as accurately as possible the heights of pressure surfaces from which the speed and direction of upper winds can be deduced.

Discussion

For current U. S. Air Force turbojet aircraft an increase in temperature requires an increase in power setting to maintain optimum cruise conditions. This increase in power setting obviously results in an increased rate of fuel consumption. The corresponding increase in true airspeed, however, is such that range is practically unaffected. Newer jet airliners will, no doubt, have the same characteristics; that is, range will not be affected provided optimum cruise procedures are followed. Earlier, less powerful turbojet aircraft such as the Comet I, for example, were unable to cruise at an optimum Mach number when the temperature was higher than standard. The change to a lower than optimum Mach number lowered the best operating altitude, the change in altitude being about 200 feet per 1° C. With the newer, more powerful jet aircraft, positive temperature anomalies do not lower the optimum altitude, since an optimum Mach number can always be maintained by increasing the power setting.

Accurate temperature measurements are required to deduce the speed and direction of upper winds over areas where they are not measured directly. An error of 1° C in measuring the mean temperature up to 40,000 feet will result in an error of roughly 20 knots in determining the mean wind speed between two radiosonde stations spaced some 300 miles apart.

Conclusions

(1) Upper level temperatures affect the optimum flight operations of turbojet aircraft. If cruise control is maintained, however, range is practically unaffected. The problem is therefore not a serious one to the meteorologist.

(2) The measurement of upper level temperatures to within ±1° C is necessary to deduce the speed and direction of upper winds by using constant-pressure charts.

Proposals

No specific proposals are deemed necessary for the observation of upper air temperature, as such, for turbojet-aircraft operation. However, the improvement in accuracy of measurements of upper air temperatures is desirable, since the information is used for deriving the speed and direction of upper air winds.

UPPER LEVEL WIND

Statement of Problem

The advent of turbojet aviation has brought with it demands for more complete and accurate knowledge of the wind fields in the upper troposphere and lower stratosphere. This is the region of optimum flight altitude for the current transport models of jet aircraft and is in the general vicinity of the midlatitude tropopause where the winds are characteristically strong. If flights of jet transports are to be planned and carried out safely and efficiently, reliable forecasts of the winds at these levels are imperative. This is especially true when strong-jet-stream conditions are involved.

The present observational system, however, is not adequate for observing and measuring these strong wind fields aloft, and present knowledge of the details of the air flow at these upper levels is still relatively poor. Therefore, weather forecasters are generally unable to produce, for turbojet operations, a completely satisfactory picture of the upper level wind field, especially in details such as the intensity and location of the maximum winds of strong jet streams.

Discussion

Because of the high fuel consumption of the turbojet engine and the relatively high fuel-to-payload ratio, it will be necessary to plan the flights more efficiently than has been done previously. Since cruise-level winds are a significant factor in flight planning, reliable forecasts will therefore play an important role in the efficient operation of jet transport aircraft.

Wind data available at the cruise level are relatively scarce, however, and, in some areas, observations are almost nonexistent. Even in areas where data are good by comparison, their reliability under the critically strong jet-stream conditions is questionable and maximums and minimums of wind speed can occur between the present observing stations and thus go unnoticed. Even though both the United States and United Kingdom are in the process of procuring or developing more adequate wind-finding equipment and recent improvements in rawinsondes have essentially increased the upper-air-network density, the quantity and quality of the wind data currently available to the forecaster under strong wind conditions still leave much to be desired.

In addition to the shortcomings of the observed wind data, the data computed from contour spacings on constant-pressure charts for these upper levels are also unreliable because of faulty heights computed by means of the hypsometric formula from erroneous radiosonde temperature data. This is due partly to differences between Weather Bureau, Air Force, and Navy instruments and partly to instrumental errors in measuring upper level temperatures, as described previously. Errors in velocity of 25 knots or more due to such causes are quite common.

A further problem that is involved in meeting the upper wind and temperature forecast requirements of jet transports is based on the rigid cruise climb path flown by these aircraft. Because the cruise consists of a continuous climb as the fuel load diminishes, no one constant-pressure chart can be used to determine the meteorological parameters required for obtaining optimum flight altitude. In order to evaluate the wind and temperature along a climbing flight path, a three-dimensional representation of isotherms and isotachs may be necessary. This will require more detailed upper level wind profiles and faster methods for computation and transmission of the upper level winds.

Conclusions

The currently obtained winds-aloft data are inadequate for the efficient and economical operation of civilian jet transports. The solution of this problem seems to depend on:

(1) Development of suitable methods and instruments for properly sampling the three-dimensional wind field at these upper levels

(2) Adequate procedures for the handling and rapid dissemination of such data

(3) Development of techniques of analysis so that the important features may be accurately determined from the data

(4) Appropriate methods of upper wind forecasting to meet the needs of jet aviation

Proposals

(1) Developments now in progress by the Signal Corps to modify the ground meteorological direction-finding type of equipment (GMD-1) by adding a ranging capability should be given top priority. Interim measures to improve the reliability of elevation-angle measurements, so critical in the present system in which slant range is not measured, should also be pursued. When this is done, it is recommended that the best equipment be made available to all forecasting services. Particular attention should be given to making the instruments used by the Weather Bureau, Air Force, and Navy the same, or at least equal and compatible. A more adequate upper air network would be desirable, especially over the oceans. In addition, automatic computation of wind speeds and directions by suitable instrumentation would be highly advantageous, in that human errors would be negligible and the time of transmission would be accelerated.

(2) Projects like those of the Navy and Air Force, using well-instrumented jet aircraft to investigate the details of the jet stream, should be encouraged. The results of such studies will indicate the important but small-scale features of the jet stream which can pass unnoticed between two regular stations of the current observational network. It may be necessary to include such details in upper-air analysis by way of aircraft observations or merely by implication once the details are understood.

(3) A more adequate winds-aloft code should be developed so that essentially complete profiles can be reproduced and important features, such as shear, will not be lost in standard-level intervals that are too gross. Since analysis and forecasts are made on the basis of pressure, significant levels should be reported using pressure altitude rather than absolute altitude, especially at levels above 25,000 feet (see section entitled "Altimetry").

Collection, evaluation, and transmission of upper air wind data should be speeded up in order that they may be of utmost value. Currently, some upper air data are more than 4 hours old when transmitted. It is recommended that wind profiles for all rawinsonde observations be transmitted in a form which provides data for both standard and significant levels (in a manner similar to that in which radiosonde data are transmitted).

(4) The development of adequate techniques for wind forecasting at upper air levels is needed. The promotion of theoretical and experimental investigations involving the dynamics of the whole upper level air flow will serve this desired aim.

(5) New methods for gathering wind data at high levels should be studied and evaluated, for example, in-flight reports from jet aircraft giving D values along the track (or height profiles additional to any radiosonde information), in-flight reports of observed winds using conventional or automatic navigational equipment, and data from constant-level balloons and their trajectories.

HIGH-LEVEL CLEAR-AIR TURBULENCE

Statement of Problem

Among the meteorological phenomena that affect the commercial turbojet aircraft at cruising levels, clear-air turbulence is undoubtedly the most troublesome. The fact that these aircraft perform most efficiently at high levels causes them to be exposed to this turbulence which is now known to occur in the upper troposphere and lower stratosphere. Unfortunately, the higher speed of these aircraft intensifies the effects of the turbulence and their narrower limits of cruising speed and altitude make avoidance of turbulence more difficult. Generally, the gusts have an adverse influence on the comfort of the passengers and contribute to structural fatigue. Occasionally, the turbulence may be severe enough to impose serious stresses on the aircraft and possible injury to the occupants. This is especially true since the rough air occurs without any visual warning and hence there is no time to take precautionary measures.

This phenomenon as yet cannot be forecast with any great accuracy, mainly because there is not a full understanding of the causes and mechanics of clear-air turbulence.

The transitory nature of this turbulence is difficult to observe with the current fixed network of aerological stations, the scheduled observations of which are widely spaced in time. In addition, there are some pertinent parameters which are not measured by the conventional upper-air observational techniques.

Discussion

At an earlier date, it was expected that the jet transport would fly over most of the adverse weather, but, since the advent of turbojet aircraft, clear-air turbulence has become a major problem. While there have been occurrences of this phenomenon reported at the levels currently used by conventional aircraft, it appears to be more prevalent at the higher cruise levels of the turbojet aircraft. In the temperate latitudes, where most of the occurrences of turbulence have been observed, the majority of cases appear to be associated with a jet stream whose altitude (average 35,000 feet) generally coincides with that at which the current turbojet aircraft show their most efficient performance. Sometimes, this association entails the interaction of upper tropospheric and lower stratospheric air in conjunction with a pronounced jet stream that involves the juxtaposition or superposition or both of the subtropical and the polar tropopauses. Clear-air turbulence is usually found in regions where steep lapse rates occur and where the wind shear, especially in the vertical, is most intense. This turbulence may also be associated with other features of the atmosphere, for example, the divergent outflow in the upper portion of cumulonimbus clouds.

Since conventional methods of upper air observations do not provide measurements of vertical or oscillatory motions of the air, they are inadequate for detecting the occurrence of this turbulence. Failure to obtain direct observational evidence of turbulence also stems from the smallness of scale and the transient nature of this phenomenon in relation, respectively, to the gross spacing of the stations in the aerological network and to the time interval between soundings. Therefore, the practical solution, in general, has been to use jet aircraft as probes to secure direct experience of turbulence. However, the problem of obtaining the antecedent and concurrent high-level synoptic meteorological data is somewhat more difficult. Specially instrumented flights from U. S. Navy's Project Arowa and U. S. Air Forces' Project Jet Stream with trained personnel have made some valuable initial efforts in this direction, but much more work along this line will be needed.

As far as theoretical considerations are concerned, there is a great deal yet to be accomplished. While present aides such as the Richardson criteria are helpful, they have proved ineffective in solving the problem. In order to be able to forecast clear-air turbulence accurately, it will be necessary to develop a theory which would provide information on the history, development, and length of duration of the turbulent manifestations, as well as on the intensity, size, and space distribution of the turbulent elements. Research relevant to this problem is currently being conducted at various institutions.

Conclusions

The existing observational and theoretical basis on which methods can be established for forecasting clear-air turbulence are found to be inadequate. It should be noted that the forecasting of this phenomenon will often necessitate the forecasting of larger features, such as the jet stream.

Proposals

(1) Investigations are now in progress for evaluating the effectiveness and the practicability of gust-alleviating devices. Some preliminary work has already been completed in this field. Research programs for the development and testing of a gust-alleviating device should be continued.

(2) Clear-air turbulence seems in the majority of cases to be associated with jet streams and in most of the remaining cases with other particular recognizable conditions of the upper air, for example, strong shear, cold lows, and so forth. Assuming the ability to forecast the occurrence of these attendant conditions, a study should be made to determine what would constitute the necessary and sufficient three-dimensional observational data to be used for developing practical rules for forecasting clear-air turbulence. Jet aircraft will probably continue to serve as probing instruments in data collecting programs, while other instruments, such as gustsondes, may need to be developed. Cognizance should be taken of such investigations as have already been initiated in this field.

(3) Theoretical and experimental investigations along lines that may be conducive to the solution of this problem should be encouraged and promoted. Guidance for this work might be secured through the medium of a competent panel of experts.

OTHER SIGNIFICANT WEATHER FACTORS

Statement of Problem

Other weather factors which may affect jet-aircraft operations are cloud turbulence, icing, visibility at upper levels, runway conditions, frost, and precipitation. The problems that these weather factors present are not expected to be different in nature from those affecting present-day conventional-aircraft operations. However, because of the higher speeds of jet aircraft, the problems associated with icing, turbulence, and hail may be more critical.

Discussion

Turbulence.- Turbulence which will affect passenger comfort but is not structurally dangerous is associated with some cirrus clouds and also with cumulus cloud masses not developed to the congestus or thunderstorm stage. In view of the greatly increased speeds of jet flight, this latter form of turbulence may be quite objectionable during ascent to or descent from cruising levels. A detailed knowledge of cloud conditions would be quite helpful in flight planning.

Turbulence which could be dangerous to jet flight occurs in connection with mountain waves and within, or just above, cumulonimbus clouds. Mountain-wave conditions can be forecast with a reasonable degree of accuracy. General areas of thunderstorm buildup can be predicted, but it appears that thunderstorm-cloud tops cannot be forecast within several thousand feet. At cruise level, aircraft can normally avoid penetrating cumulonimbus clouds, thereby avoiding the dangerous turbulence, except during periods when the tops of these clouds are obscured by cirrus or haze layers. Occasionally squall lines may pose an impenetrable barrier.

Icing.- From current information, it appears that the probability of occurrence of meteorological conditions conducive to ice formation at the cruise levels of turbojet aircraft will be lower than the probability at the present cruise levels. Significant icing intensities as may occur at turbojet-aircraft cruise levels will, in most cases, be associated with cumulonimbus clouds. Flight penetration into such clouds, if they are detectable, will usually be avoided for other reasons, such as turbulence. Therefore, encounters of serious icing intensities at high altitude can be expected to be very infrequent.

At the lower flight levels, the operation of turbojet aircraft equipped with protection systems should present no new icing problems for the forecaster.

Conclusions

The salient problem considered in this section and the one most likely to assume critical importance in any future large-scale jet-aircraft operations is that of thunderstorm turbulence. In view of the physical nature of thunderstorm development, it appears unlikely that precise forecasts of the locations of individual or even groups of thunderstorms will ever be possible, much less any accurate prediction of their individual intensity. Future progress will probably depend upon the utilization of airborne and ground radar of suitable characteristics.

Proposals

(1) The development of a satisfactory airborne weather radar for use on transport jet aircraft should be enthusiastically pressed forward; flight experience in the utilization of such radar for avoidance of turbulence, hail, and icing associated with well-developed cumuloform clouds should be accumulated without delay.

(2) Procedures should be developed to permit better utilization of surveillance radar now in operation by both military and civil agencies. This required provision of direct radio communication between the aircraft in flight and the surveillance radar facilities which can be of value to the pilot. For maximum value to the pilot, provision should be made to relay traffic-control clearances through the radar facilities being used by the flight. Such procedures are now in use by the Civil Aeronautics Administration and certain military surveillance radar facilities and should be expanded as rapidly as possible. Not only will turbojet-transport operations benefit, but small military and civil aircraft not equipped with airborne radar to display the more treacherous cumuloform clouds will also be aided by such a system.

RELEVANT OPERATIONS PROBLEMS

Communications

There are several other problems associated with the safe, efficient, and economical operation of aircraft which have less meteorological significance; of these the communication problem is probably the foremost example. For turbojet-aircraft operation, speedy and reliable radio communication is essential; the transmission of the terminal forecasts or other operational advice to the pilot during flight and just prior to descent should be uninterrupted. As communications utilizing L/MF and HF are readily susceptible to atmospheric and precipitation static, it is urged that VHF or UHF communications and navigation systems, either of which is infrequently affected by by static, be available for use by jet aircraft. Careful attention must be paid to the need for special frequencies for communication with jet aircraft because of the height of the aircraft and the communication interference that results from stations operating on the same frequency. It is apparent that jet aircraft must have more frequencies available than aircraft operating only at lower latitudes.

Air Traffic Control

During periods of adverse weather, with particularly low ceilings and visibilities, traffic-control problems at or near airports are increased, and with the expected mixed traffic (piston and jet aircraft) these problems will be intensified. In addition to the number of aircraft utilizing an airport, time-consuming instrument letdown procedures, missed approaches, emergencies, or completely closed airports all contribute to traffic congestion. To alleviate this congested traffic, the use of automatic equipment, radar, and other devices is being pursued.

All efficient turbojet-aircraft operations will probably be conducted under Instrument Flight Rules so that the traffic will be more completely controlled. Weather forecasts and observations, both at the terminal and en route, will require more accuracy, a requirement that is also needed today.

Ground Radar

For all-weather flight, full utilization of approach and landing aids is required. Heavy precipitation clutters the surveillance and precision plan-position-indicator (PPI) radar scopes. Until such time as radar beacons for traffic control are installed in duplicate in all aircraft, there will be a demand for accurate forecasts of heavy precipitation. Many small jet aircraft may not be able to carry a beacon at all. Heavy precipitation will always cause a decrease in effectiveness of approach and threshold lighting. The need for precise forecasts of the amount and kind of precipitation will continue to increase on this account. rate?

Noise

The aircraft and airport noise problem also has the weather factor involved. Although research is continuing on the fundamentals of the generation, propagation, and reduction of aircraft noise, it appears that many years will pass beofre noise-reduction methods may be applied without performance loss; meanwhile, engines are becoming more powerful. The influence of atmospheric factors (properties of the medium, temperature, wind velocity gradients, turbulence) on sound propagation is presently under study. It may not be amiss to predict that the results of noise-propagation investigations may indicate relationships between sound and weather, that some noise alleviation or increase may be achieved under certain meteorological conditions, such as temperature inversion and wind gradient, and that the airport management may eventually seek information from the weather office for the purpose of noise control.

Altimetry

Higher flight speeds and altitudes may pose an altimetry problem for turbojet-aircraft operation, inasmuch as the barometric-pressure type of altimeter may not be sufficiently accurate at very high altitudes for normal vertical separation of aircraft. In addition, at high flight speeds, manual setting of the barometric-pressure type of altimeter may become more than a nuisance to pilots.

Present practice is for aircraft to fly with respect to pressure altitude (altimeter setting 29.92 inches) at all levels over oceans, whereas over land, "controlled" flights are made with respect to a pseudo-true altitude which is actually pressure altitude plus the D value at the surface. At high altitudes, deviations from true altitude may often be greater with the altimeter set according to the ground pressure than with it set at 29.92 inches. For greater convenience and more accurate forecasts of wind and temperature, turbojet-transport flights above 25,000 feet over land should also be conducted with respect to pressure altitude. If this were done, high-altitude winds would be reported in the same system, that is, pressure altitude rather than geometrical altitude, as at present. This method would yield more accurate wind forecasts for flight operation.

CONCLUDING REMARKS

In general, it is concluded that, although the weather-service requirements for turbojet-transport operations will be somewhat different from those for current aircraft, the difference will be mainly one of scale rather than of scope. No new requirements are anticipated even though operating altitudes and speeds are increased and forecast-error limitations are more critical. The meteorological problems, therefore, will be rather similar in nature to the present ones.

The recommended solutions for these meteorological problems involve adequate instrumentation properly placed to obtain more accurate and representative data at all levels, improved methods for more rapid collection and dissemination of data and information, reliable techniques for analysis and forecasting, and the successful application of research results.

NACA Headquarters,
Washington, D. C., November 1, 1954.

APPENDIX A

WORKING-GROUP MEMBERSHIP

The members of the working group were the following:

Lt. Col. Olav Njus, USAF, Chairman - Air Weather Service
Mr. LeRoy H. Clem, Chairman - U. S. Weather Bureau
Lt. Col. Arthur F. Gustafson, USAF - Air Weather Service
Comdr. Daniel F. Rex, USN - Office of Chief of Naval Operations, Aerology
Comdr. Charles R. Dale, USN - Office of Chief of Naval Operations, Aerology
Mr. Frank C. White - Air Transport Association
Mr. Robert M. Rados - Air Force Cambridge Research Center, Geophysics Research Directorate
Mr. Daniel M. O'Keefe - Capital Airlines, Inc.
Mr. Mason T. Charak, Secretary - NACA Headquarters

Mr. Clem was elected chairman at the fifth meeting on April 27, 1954, succeeding Lt. Col. Njus. Lt. Col. Gustafson replaced Lt. Col. N, as the Air Weather Service representative in May 1954. Comdr. Dale replaced Comdr. Rex as the Navy member in July 1954.

Mr. Louis P. Harrison, U. S. Weather Bureau, served as permanent consultant to the working group.

Mr. Henry T. Harrison, Jr., United Air Lines, Inc., aided in formu lating the statement of the problem.

The following specialists attended one or more meetings of the working group:

Captain Keith Veigas, USAF - MacDill Air Force Base
Mr. Harry Press - NACA Langley Laboratory
Mr. Boyd C. Myers, II - NACA Headquarters

APPENDIX B

FORECAST OF METEOROLOGICAL PARAMETERS FOR JET-AIRCRAFT OPERATION

TAKE-OFF AND LANDING FORECASTS

Surface Temperature

To determine the length of runway needed to take off and to clear all obstacles by 50 feet at a given take-off weight, the runway pressure altitude, the air temperature, and the wind component along the runway should be known. For those bases where runway length is critical, air temperature over the runway at about the jet intake level must be known to an accuracy of approximately $\pm 5^{\circ}$ F. For the Comet I, if temperature is considered the only variable and a reasonable gross weight is assumed, this is equivalent to predicting take-off roll to about ± 200 feet or take-off gross weight to about 1,000 pounds. Figures available on other jet transports indicate that a $\pm 5^{\circ}$ F change in temperature would have a somewhat smaller effect on take-off roll distance, but the effect on gross weight would be about three times as large, or about 2,500 pounds. When the other variables in calculating take-off roll distance are considered, a more exact value of temperature will not result in a significantly better value for the calculated take-off roll. This information must be available 1 to 2 hours before take-off and again, for verification purposes, just prior to take-off. A forecast of runway temperature is also required about 12 hours before take-off. This forecast should be as accurate as possible, but forecast errors of $\pm 10^{\circ}$ F are tolerable.

Surface Humidity

The British experience with the Comet (refs. 3 to 8) is that no evidence whatever has been found that humidity has any noticeable effect on take-off performance.

Surface Pressure

Air pressure is the third important variable in determining performance. Under conditions where runway length is critical, a change of 10 millibars in the surface pressure, temperature remaining constant, will have about the same effect on the take-off roll distance as a change of 5° F at constant pressure.

Pressure Altitude

There is a 1:1 correspondence between pressure and pressure altitude as determined by the standard atmosphere; and for practical reasons aircraft performance manuals are based on pressure altitude as one of the fundamental parameters. Since the variables temperature, pressure altitude, and wind determine the length of the take-off roll or the maximum gross take-off weight, it is convenient to provide forecasts of pressure altitude as well as of temperature and wind. Under conditions when runway length is critical, that is, high temperature and low wind speeds, pressure altitude can be forecast quite accurately. Figures available on two types of jet aircraft show that the effect on take-off roll of a 500-foot change in pressure altitude at constant temperature is about the same as a 10° F change in temperature at constant pressure altitude. Assuming that the same relationship holds true for other types of jet aircraft, pressure-altitude forecasts accurate to ±250 feet will satisfy the requirements.

Ceiling and Visibility

Reliable ceiling and visibility forecasts are required, for, when low ceiling or visibility prevents or delays take-off or landing, even small forecast errors are costly. The real problem is to determine how accurately ceiling and visibility can be forecast and adjust operations to these errors. Planning forecasts will be required well in advance of take-off and verifications on the basis of latest observations will be necessary at departure time. The landing forecast is even more critical than the take-off forecast and, to provide a forecast of maximum accuracy, the forecast period must be reduced to a minimum. This necessitates rapid and reliable communications so that a last-minute landing forecast can be provided before the pilot begins the descent to the terminal selected for the landing. To provide a maximum degree of safety, forecasts of the alternate-terminal conditions will also be required at this point.

Wind

Forecasts of the following wind conditions are required:

(1) Wind speed parallel to the runway - The wind speed parallel to the runway affects the length of the take-off roll or the maximum gross take-off weight; so, when runway length is critical, an accurate forecast of the wind speed parallel to the runway is required. If take-off distance and temperature are held constant, a 10-knot increase in headwind will permit one type of jet transport aircraft to take off with 12,000 to 13,000 pounds more gross weight. For a given gross weight, take-off

roll is decreased 700 to 1,000 feet for each 10-knot increase in take-off headwind. These figures show that a 2-knot headwind will have about the same effect on take-off roll or gross take-off weight as a 5° F temperature change, that is, roll decreases 200 feet or less or take-off gross weight increases 2,500 pounds. (To see further the interdependence of forecast errors, 2,500 pounds of fuel will be sufficient to take care of a 25- to 50-knot error in the mean-route-wind forecast over a specified sector length.) The effect on landing is less.

(2) Crosswind component - With a high crosswind component, landing of aircraft is critical and becomes impracticable if the crosswind component exceeds certain limits. The limit of safety depends upon the gustiness of the wind; maximum crosswind components are tolerable if the wind velocity is steady. Therefore, accurate forecasts of crosswind components are desirable. It is not possible to arrive objectively at the desired accuracy, but experience indicates that forecasts and observations accurate to ±5 knots would be adequate.

(3) Gustiness - As with piston-engine aircraft, the gustiness of the surface wind is important to take-off and landing of jet transport aircraft. The effect of gusts on an aircraft becomes increasingly critical (a) as the difference between the indicated airspeed on the final approach and the indicated airspeed at touchdown decreases and (b) when the wings of the aircraft are low so that a slight "tip" of the aircraft will cause the wing tips to strike the ground.

The design of present-day jet transports is such that gusty surface winds are more critical than for most piston-engine aircraft. The specific requirement for forecasts or observations or both of surface gustiness cannot be determined objectively. However, gustiness expressed at maximum wind speed recorded over a period of about 5 minutes is apparently needed. It is evident that forecasts of critical gustiness would be required 12 hours, 1 hour, and just prior to take-off and landing.

ASCENT AND DESCENT (SURFACE TO APPROXIMATELY 35,000 FEET)

Mean Wind and Mean Temperature

A forecast of the mean wind from the surface to 35,000 feet in altitude increments is required. Mean-temperature forecasts are desirable. In both cases, accuracy is important but not critical.

Expected Weather Conditions

Except for icing, turbulence, and hail associated with thunderstorms, weather for ascent and descent does not appear critical.

CRUISE

Wind

A mean-wind forecast for the entire route is required, sufficiently accurate so that excessive fuel loads are not necessary. Generally, it is considered that a mean wind accurate to ±10 knots is desirable. This wind forecast must be prepared and presented in sufficient detail so that horizontal and vertical diversion to take advantage of favorable winds is possible. (Figures available for the Comet state that vertical diversion is profitable if the wind shear at the optimum cruise level exceeds 10 knots per 1,000 feet.) In addition to supplying the information necessary for planning minimum flights, the wind forecast must provide the information needed if diversion, both vertical and horizontal, becomes necessary (i.e., because of engine failure). The wind required is not a constant-level wind, since a jet in normal flight maintains a slow climb.

Temperature

Temperature at all altitudes affects turbojet-engine performance. However, if proper cruise control is maintained, range is practically unaffected; thus, the problem is not a serious one for the forecaster. It is generally assumed that forecasts of temperature accurate to $\pm 5^{\circ}$ C will be needed.

Other Conditions

Turbulence and icing are two meteorological phenomena which require forecasts so that safe, efficient, and comfortable flight plans may be maintained. Dangerous turbulence may be encountered in cumulonimbus buildups, in mountain waves, and in clear air. Icing conditions at jet-aircraft cruise levels are likely only in cumulonimbus clouds. Forecasts of areas of turbulence or icing (or both) are important so that these areas may be avoided and allowed for in fuel-supply calculations.

APPENDIX C

DISCUSSION OF CEILING AND VISIBILITY PROBLEMS

REQUIREMENTS DURING AN APPROACH

The most crucial problems relate to the forecasting of conditions that will be encountered over the surrounding terrain and the runway during the approach for a landing and during the touchdown and landing-roll periods (ref. 1). Upon breaking these problems into constituent parts (ref. 9) it will be noted that during the latter portion of the approach while still above critical altitude the pilot must first secure visual reference with respect to the terrain or approach-light system to permit him to check his altitude and location with respect to the runway and, then, upon passing below the critical altitude, to make proper and timely modification of the control settings of his aircraft, if necessary, taking account of heading, horizon, attitude, and height to reach the touchdown point in a normal manner. Next, the pilot must visually detect and recognize the threshold of the runway and see enough of the runway to orient for the final landing maneuver and to effect a touchdown safely. So far, it will be noted that the problem involves slant visual ranges of certain specified targets as observed by the pilot from a succession of points on the glide path. Finally, after touchdown, the horizontal visual range along the runway concerns the pilot, for he must see markings or lights enough distance ahead along the runway to complete the landing roll safely. The minimum distance has been variously estimated from about the linear displacement of the aircraft in 3 seconds at constant speed to about 1,200 feet.

PROBLEM OF SLANT VISUAL RANGE

In the case of the approach, the vantage points from which the pilot makes slant visual reference are in the free air at various positions on the glide path. Unfortunately, the slant visual ranges involved here are not, strictly speaking, uniquely determined by the cloud-base height (ceiling) and the horizontal visibility. Pointwise, those ranges are governed physically by the slant transmission of light in the atmosphere and the inherent contrasts of the target against its background or the intensity of the light source observed. Psychophysically, the ranges are determined by the adaptation of the pilot's eyes for the detection and recognition of apparent contrasts of runways or other targets against their background or for the detection and recognition of lights. The adaptation of the pilot's eyes depends largely on the background brightness to which they have been exposed and on sources of glare. Some of the additional factors are cockpit cutoff; rain, ice, or snow on the windshield; turbulence; ground speed; familiarity of the pilot with the terrain environment of the airport; landing-aid facilities; use of manual or automatic approach control couplers; and so forth. These factors greatly affect the search time for detecting approach lights, landmarks, and runway threshold.

PROBLEMS OF VARIABILITY

The variability of the atmosphere both in space and time with regard to clouds, fog, haze, smoke, and various forms of precipitation that act as obstructions to vision hampers the expression of slant visual range or runway visual range by a simple specification. Super-imposed on the foregoing are the variabilities of the background brightness and glare conditions, as well as the state of the pilot's eyes, which control his ability to see. Beyond these, there occur the variabilities in the other factors mentioned above.

Studies made by various organizations have shown that cloud bases generally exhibit pronounced irregularities, such as pendants and hollows (refs. 10 and 11), which may be transported by the cloud movement and which also may be affected by precipitation and by convective currents. These currents, and hence the distribution of pendants and hollows, are partly controlled by the orographic features of the area traversed. Thus, ceiling measurement is a variable which may be regarded as stochastic, with apparently random variations.

The probability of an aircraft breaking out of an irregular cloud base within a particular altitude range is therefore a matter that depends upon the frequency of various cloud-base heights. Some concept of this frequency may be gained by a detailed study of the progression of cloud-base heights indicated by the rotating-beam ceilometer, while a measure of the variability is yielded by the moving successive standard deviations of the cloud-base heights. These facts point to the conclusion that the determination of these standard deviations would provide useful information pertinent to the problem (see refs. 9 to 12).

From the foregoing discussion, it appears that the best that could be expected by way of a forecast is a set of statements of the probabilities that the ceilings and visual ranges will lie between certain limits, assuming certain psychophysical parameters and functions to be known.

MEASUREMENT OF SLANT TRANSMISSION

Slant visual range involves the transmission of light through inclined paths. In order to measure this transmission, it is necessary, in general, to observe from the surface, since it is impracticable to mount instruments or place observers in the free air at the points on the glide path that will be followed by an aircraft during a descent. Stewart, Drummeter, and Pearson (ref. 13) have developed a method of measuring slant transmission based on photometric measurements at two points on the surface of light scattered from a searchlight beam. Middleton (ref. 2) has made calculations to determine whether photomultiplier tubes are sensitive enough to permit making these photometric measurements under dense fog conditions, and he has come to negative conclusions.

AUXILIARY DATA FOR SLANT VISUAL RANGE

Apart from the need for optical transmission data pertaining to slant range, there is a need for measurements of a different character, such as of the luminance (photometric brightness) of the background or horizon, against which objects on the ground are seen by the pilot, and the illumination incident on a horizontal surface. Observations of this character provide a basis in calculations for the brightness contrasts with which the pilot may be confronted and for the background brightness to which the pilot's eyes may be adapted. Additionally, the intensities of point sources of light must be determined for various directions of propagation, and likewise similar data for glare sources, whether from the sun or artificial lights, must be known. Information of this nature is essential for visibility computations involving lights. (Further details are presented later.)

PROBLEMS OF HORIZONTAL VISIBILITY

With regard to horizontal visibility, tests have been conducted (refs. 9 to 12) to ascertain the utility of an instrument, called a transmissometer installed near the touchdown point, for measuring horizontal transmission over a 750-foot baseline. Results of the tests show that significant deviations can occur between results given by direct visual observation from a fixed point and those given by the instrument, assuming certain calibration constants. Part of the deviations can be considered to arise from variations in performance of the observers (psychophysical factors) part can be attributed to imperfect sampling by the instrument (limited to a 750-foot path) when the atmosphere is not optically homogeneous, and part can be traced to lack of similitude of light and background conditions between observer and instrument.

As demonstrated by these tests, the raw data yielded by the transmissometer are often not representative of the horizontal projected distance from the runway threshold to the point on the glide path at which the pilot first sees the threshold. This means that the presence of cloud, fog, haze, and precipitation, above the transmissometer level, and factors such as cockpit cutoff, glare, rain on the windshield, and so forth, which cannot be taken into cognizance in the instrument calibration, exert a profound influence on the results. That is, the transmissometer by itself gives an imperfect and incomplete presentation of the visibility conditions confronting the pilot while airborne, especially if there are obstructions to vision aloft. However, when there is homogeneous, low-lying fog, the transmissometer is capable of giving fairly representative results.

SYSTEM PROPOSED BY SPERRY GYROSCOPE COMPANY

The Sperry Gyroscope Company has proposed a system of estimating the altitudes at which the pilot will first establish (a) vertical visual contact with the ground and (b) slant visual contact with the runway threshold. This system requires, first of all, classification of the weather conditions into categories such as low clouds, radiation fog, and snow. A different evaluation chart is used for making the estimates pertaining to each category. The category must be ascertained by the observer from a consideration of the current synoptic chart and the weather conditions at the terminal. Among the parameters that must be measured are (1) the horizontal transmissivity, (2) the mean cloud-base height determined by averaging about eight indications of the rotating-beam ceilometer, (3) the standard deviation of the cloud-base height established from these indications, (4) the background luminance (photometric brightness), and (5) the illumination incident on a horizontal surface at the ground. Consideration must be given to the objects in the approach area with regard to their size, inherent brightness, and reflectance, or intensity and glare source in the case of lights. This requires a separate calibration at each major terminal. Also involved are transient variables such as the presence of ice or snow on the ground and on the runway, the occurrence of a sheet of water on the latter, the intensity setting of the approach lights, and the direction of the sun in some circumstances.

The system referred to above has been developed only at MacArthur Airport, New York, using a DC-3 aircraft equipped with an automatic-approach coupler and operated by a special crew having long experience.

A scanty collection of comparative test data has also been secured for Idlewild International Airport, New York, on a few occasions. How well the system will work under diverse conditions as regards weather category, aircraft, pilots, approach-light system, and so on remains to be determined. Owing to the fact that the system entails some empirical relationships and does not involve actual slant-transmission measurements, it appears that something would be left to be desired even if the system were introduced.

One salient fact concerning the system must be emphasized, namely, that it is based essentially on current observations; hence, it is not intended to yield forecasts of certain visibility representations of interest to the pilot if the basic parameters used in the system suffer a significant change. Thus, there remains a requirement for forecasts of the parameters.

HUMAN VERSUS INSTRUMENTAL VISIBILITY OBSERVATIONS

With respect to visibility, experience in the United Kingdom (ref. 14) has led meteorologists and aviators there to stress the importance for landing purposes of "runway visual range" in lieu of "meteorological visibility," or visibility observed from a station. Runway visual range is determined by an observer located at the end of the runway, facing in the direction of landing, and observing the greatest distance at which runway lights or markers at the side of the runway are visible. The markers are shaped like A tents, with half of each sloping face painted black and half painted white.

In the United States the inclination has been to use a device, namely, the transmissometer, installed near the end of the runway to yield "horizontal visibility." The result obtained depends upon the calibration assumed for the device and is limited by conditions along the sampling path (750 feet). When conditions are not homogeneous, the value of visibility calculated from the path transmission may be sometimes less and sometimes more than the visibility that would be reported by an observer who integrates over a longer (or shorter) horizontal distance. The observer can take account of effects of glare, directional intensities of lights, background luminance, and so forth. The transmissometer by itself cannot do this. However, should there be an addition of certain auxiliary illumination and photometric devices in conjunction with calibration of the light sources, target characteristics, and other factors, significant improvements may be possible.

One conclusion that has received considerable support from several studies is that the prevailing visibility (ref. 15) estimated by an observer at a meteorological station on the basis of the conditions over half or more of the horizon may in many circumstances yield results not representative of runway visual range. Therefore, some improvement may be achieved by giving pilots reliable reports of runway visual range for the landing area to assist in the final approach and touchdown. Such a measure is very important safetywise for high-speed aircraft descending towards short runways, especially with a low ceiling and low visibility weather situation. This is particularly true if there are tail winds or strong cross-runway winds. Experience at MacArthur Airport has shown that a severe wind shear accompanied by turbulence in the lower 1,000-foot layer of the approach poses difficult control problems in this region and hazardous landing conditions, which become greatly aggravated under the circumstances described immediately above.

ADEQUATE NETWORKS, OBSERVATIONS, AND FORECASTS

While frequent, reliable end-of-runway and approach-zone observations of ceiling and visibility are necessary as a foundation for services to both jet and conventional aircraft under instrument weather conditions, these observations are not enough to satisfy all the requirements by themselves, as previously indicated. First of all, observations of supplementary and additional parameters are desirable to bolster the program. Second, the concept of a single station as a basis might be expanded in scope to include a small grid of outlying nearby points from which observations are secured by suitable communications mediums to detect movements of fronts, cloud systems, precipitation, and so forth into the area. Third, the combination of all available data, including those from the synoptic network, severe-storm local reporting networks, and others, must be converted into suitable forecasts for the purposes and time intervals outlined in the early portion of this discussion. Fourth, the pertinent forecasts and latest end-of-runway observations must be communicated by radio to the pilots at appropriate times.

Appendix D illustrates in outline form some of the facilities, equipments, and supplementary observations which might be contemplated under an idealized program designed to provide, in the long range, a sound basis for a system capable of yielding significantly improved forecasts. Underlying the material in appendix D is the view that the physical factors and processes involved in fog and cloud formations, precipitation, smoke diffusion, dust and haze transport, and other phenomena must be observed directly, if possible, and taken into account explicitly if real progress is to be made in forecasting for the specified purposes. The size of the network of stations which must be embraced in the system will depend, naturally, upon the range and time interval covered by the forecasts. Thus, for the 5- to 7-day forecasts, hemispherical and global extents are entailed. For the 24-hour forecasts, areas within radial distances of one-half to perhaps one-fourth of these will be involved. For the

6-hour terminal forecasts, radial distances of the order of 1,000 to 2,000 miles will come into consideration. In the case of the 1-hour forecasts, radial distances out to several hundred miles will have to be covered; and, finally, with regard to the forecasts covering a 20-minute range, distances out to perhaps 50 miles will be of concern. However, the optimum density of the network for these various ranges or time intervals is not uniform, for a denser distribution is necessary in the immediate vicinity of the terminal to enhance the accuracy of the short-time, local forecasts.

By a suitable design of the network spacing and station locations, the spectral distribution of sizes of the weather systems which affect the terminal can be brought into consideration, so that greater detail is secured where needed. The question of what constitutes an adequate network for specific purposes deserves much consideration in the long range. Study of the problem of the best strategy for location of stations may be accomplished by the methods of operations research. Investigations to this end must take account of orographic influences and local factors such as those which are conducive to fog formation or thunderstorm outbreaks. Trends, gradients, and other derived functions with respect to the various parameters of concern will have to be ascertained from the networks to permit forecasts of development phenomena.

A soundly established service to achieve results significantly better than those heretofore secured must allow for the volume of material that will be collected and the speed with which the weather analyses and forecasts must be issued. This will call for high-speed methods for collecting, processing, and issuing data. Specialized equipment and personnel will doubtless be required to cope with each phase of the program. To a considerable extent the schedule of observations and issuance of reports must be geared to meet the traffic requirements and it must be capable of adjustment to yield optimum results by variations in frequency, content, areal coverage, and so forth as may be called for to fulfill best the needs of the situation.

Confronted by a requirement to maintain a continuous watch on weather for the ranges outlined above, the meteorologist must have at his disposal a communications system which is utterly reliable and a reporting system which signals significant changes that may determine instrument weather at the terminal and alternate over the operating time interval.

DEVELOPMENTS REGARDING VISIBILITY

While the forecast of clouds and weather to be expected is an essential basis for a solution of the problem, there still remain the questions of determining the probabilities of the various possible slant visual ranges, ceilings, and surface horizontal visibilities that will be encountered in an approach at a given terminal. Progress in these directions will require not only improved measuring techniques and more extensive observational determination of parameters but also improved theory (ref. 16), especially in regard to slant range and horizontal visibility from moving aircraft under nonhomogeneous conditions, with various foregrounds and backgrounds. It will also be necessary to take account of many factors usually neglected, such as effect of type of approach coupler (manual or automatic) on search time, effect of rain or snow on the windshield, effect of glare sources, and cockpit cutoff (ref. 17).

SUGGESTIONS FOR RESEARCH AND DEVELOPMENT

Before an efficient meteorological service for civil turbojet aircraft can be put into effect in the United States on an economic basis, some experience for providing the necessary service seems to be called for on a small scale. This experience should be gained prior to the inauguration of flights on a regular, full schedule, so as to establish a foundation on which to construct a secure organization in the future, capable of yielding reliable forecasts of the variable parameters governing the required elements and of issuing prompt predictions of the appropriate ceilings and visibilities.

To aid in improving the overall problem of forecasting the terminal ceiling and visibility (including slant visual range), the following specific tasks are suggested:

(1) Development and testing of various new or improved ceilometers; testing effect of varying base line

(2) Development of slant-transmission measuring methods under low visibility and ceiling conditions, giving consideration to use of high-intensity, intermittent "flash" types of light sources for the searchlight projector

(3) Development of various new or improved methods for securing permanent records of ceiling and of making automatic calculations of mean cloud-base height and its standard deviation over various time intervals

(4) Development of methods of making appropriate, automatically registered illumination and photometric measurements at the surface for the purposes of implementing horizontal- and slant-visibility determinations by instrumental means

(5) Development of methods for automatic calculation of horizontal and slant visual ranges by suitable combinations of transmission-, illumination-, and photometric-measurement data

(6) Development of methods of improved measurement sampling in regard to the variables which govern horizontal and slant visual ranges, especially when conditions are not homogeneous

(7) Development of the most efficient, systematic methods for determination of photometric properties of surfaces and lights in approach zones, runways, and landing-area environments for calibration purposes, with a view to use of the data in calculation of horizontal and slant visual ranges

SUGGESTED PROTOTYPE METEOROLOGICAL STATION

A special model meteorological office and station with associated communication facilities might be established in the field for the purposes of (a) gaining experience in the provision of ceiling, visibility, and other forecasts for jet aircraft and (b) conducting systematic local forecasting investigations to these ends, on the condition that the measuring devices and techniques are developed. Among the specific tasks would be:

(1) Install a "local grid" group of outpost or satellite stations associated with the key model station, with equipment to measure the necessary parameters and communicate the data automatically from a distance to the key station, the purpose being to permit determination of such arguments as depend upon finite differences between the data for adjacent stations (e.g., gradients, vorticities, etc.)

(2) Carry out local forecasting investigations and endeavor to develop systematic modus operandi having wide applicabilities in this field, particularly with a view to utilization of the results to provide approach and landing forecasts of ceiling, visibility, and related elements

(3) Develop methods of taking probabilities into account in evaluating and expressing forecasts; devise objective methods of assessing the expected reliability or "goodness of fit" of any given forecast

(4) Investigate various ways of rendering reports and forecasts of approach and landing conditions to aircraft pilots, with a view to presenting the information in a manner best calculated to meet the requirements of pilots, traffic-control officials, dispatchers, and others.

(5) In conjunction with reports by pilots regarding approaches of commercial or special-project flight aircraft, study the effectiveness of the system of weather reports and forecasts from the points of view of reliability and representativeness; gather and analyze approach-success statistics in this connection

APPENDIX D

IDEALIZED AIRPORT STATION WITH OPTIMUM FACILITIES

Some of the facilities, equipments, and supplementary observations which might be contemplated under an idealized program designed to provide a sound basis for a system capable of yielding significantly improved forecasts are given as follows:

AIRPORT STATION, REMOTE OUTPOST STATIONS, AND RELEVANT EQUIPMENT

The stations and relevant equipment are as follows:

(1) Buildings and facilities

(2) Power supply

(3) Ceiling measurement equipment and recorders

(4) Cloud-survey equipment (for coverage, etc.)

(5) Temperature and dewpoint measuring equipment (remote reading)

(6) Wind and turbulence measuring equipment

(7) Fog measuring equipment
   (a) Fog depth
   (b) Fog density; water content
   (c) Drop-size spectrum analyzer

(8) Precipitation-versus-time measuring equipment

(9) Transmissometer (directional, if possible)

(10) Telephotometer and photometer

(11) Illuminometer (wide range)

(12) Reflectometer for surface albedo

(13) High-intensity, intermittent light projector station

(14) Dual-station telephotometer system for slant-range determinations

(15) Polar-scattering measuring device

(16) Dust counter and pollution measuring device

(17) Nuclei counters

(18) Radar

(19) Visibility markers and standard visibility lights

(20) Microbarographs

(21) Low-level sounding and wind-finding equipment

(22) Additional observation equipment

(23) Local data recording, memory, and storage systems

(24) Local data processing devices

(25) Coding devices

(26) Maintenance personnel and supplies

(27) Transportation facilities

MEASUREMENTS AND OBSERVATIONS

The high-speed measurements and observations are as follows:

(1) Ceiling height and its variations

(2) Cloud amount; fog coverage

(3) Cloud types

(4) Cloud speed and direction

(5) General cloud survey (squall clouds, thunderstorms, front passage, dust clouds, evidence of trends, differences in various sectors, etc.)

(6) Temperature and dewpoint at two levels

(7) Wind speed; wind direction; turbulence at two levels; wind shifts

(8) Fog depth, if known

(9) Precipitation (kind, intensity, fluctuations, and duration)

(10) Obstructions to vision (fog, smoke, blowing dust, blowing snow, and precipitation)

(11) Fog density, smoke density, and so forth

(12) Drop-size spectra of fog

(13) Transmission of light over horizontal path

(14) Background luminance

(15) Horizon luminance

(16) Albedo of surface

(17) Albedo of background

(18) Slant-path transmission as a function of altitude up to 50 to 100 or more meters

(19) Polar-scattering measurements of aerosol

(20) Atmospheric-pollution concentration

(21) Hygroscopic-nuclei counts

(22) Freezing-nuclei counts

(23) Radar surveys

(24) End-of-runway observations of runway visual range

(25) Microbarograph observations

(26) Radiation from surface

(27) Additional surface measurements

(28) Low-level soundings and wind finding (hourly, if necessary, during critical periods)

(29) High-level soundings and wind finding at 6-hour intervals

(30) Pilots' reports

(31) Severe-storm and special observation network reports

TELECOMMUNICATIONS SYSTEMS

The telecommunications systems are as follows:

(1) Data collecting systems from local satellite network

(2) Data collecting systems from surrounding special warning network

(3) Data collecting systems from possible alternate terminals

(4) Data collecting systems from general synoptic and upper air networks

(5) Memory systems; data recorders

(6) Voice communications channels

(7) Data transcribing devices

They should differentiate between lab instruments and field instruments (much of above mentioned equipment hasn't reached a good lab stage much less the field stage) for interim usage.

How about additional technical personnel needed to run and maintain this ideal station equipment. Has anything been proposed to accelerate training or availability of such people? (Interim measures?)

Why not start with interim proposals and carry them out using present equipment with minor modifications.

Apparently this is total proposal report and not interim proposal.

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